

Title: Electrically enhanced *in situ* remediation of contaminated soil

The invention relates to a method of electrically enhanced *in situ* soil remediation. The invention further relates to a system and apparatus for employing such a method.

US patent No 5,433,829 (incorporated herein by reference), by the 5 same inventor as the present invention, describes a method of electroreclamation, which involves inducing *in situ* movement of undesired ions (ion complexes and electrical charged particles) and through soil under the influence of electric fields. This realized by inserting a grid of anodes and cathodes in the ground, or, when there is groundwater movement, by inserting 10 a screen of alternate anodes transverse to the groundwater stream direction. Similar techniques are described in US 5,589,056 and US 5,846,393.

Other electro-remediation techniques (not described in US patent No 5,433,829) include electrically enhanced phyto-remediation and bio-reclamation. Phyto-remediation involves planting and harvesting plants that 15 take up ions and ion complexes from the soil, wherein spatial extent of the uptake is increased by moving ions and ion complexes in the soil around the roots of the plants under influence of electric fields. Bio-reclamation involves electrically heating the soil to increase the speed at which chemical/physical reactions and/or biological activity removes undesired material.

20 *In situ* electroremediation usually involves the generation of electric fields over a considerable extent of land, typically tens or even hundreds of meters, and over a considerable duration of time, typically months or even years. In order to make such a process economically viable it is desirable to use as few and as simple electrodes as possible and to pass as high currents as 25 usefully possible through these electrodes. Also, a considerable amount of electric energy is used. It is desirable that this energy should be used efficiently as possible.

Another cost factor is the cost of human intervention or supervision during operation over such long time and large area's. The equipment used to perform the process should be able to operate automatically, with a minimum of human intervention or supervision. This can be difficult, because the 5 behaviour of the remediation process over such large, inevitably not entirely homogeneous land areas and such long time scales is not entirely predictable.

One important factor during automatic operation is protection against electrode failure. US 5,433,829 describes various techniques to guard proper operation of the electrodes. One technique involves keeping a record of 10 cumulative service life of each electrode in order to select a time for replacing the electrodes. US 5,433,829 also describes that clogging of the cathodes by the precipitation of hydroxides on or near the cathode may hamper proper operation of the remediation process. Clogging occurs when a DC current is applied through an electrode for longer durations. Clogging can make a 15 cathode useless and it can increase the resistance between anodes and cathodes, so that an increasing amount of energy is wasted by increasing heat production in the electrode filter. Similar clogging problems may occur at the anodes due to acid formation.

US 5,433,829 describes how clogging can be prevented by 20 incorporating each electrode (anode and/or cathode) in a housing in which liquid is circulated, the housing being permeable for charged particles, but much less permeable for the bulk of the liquid, and inserting the electrodes into the ground with their housing. Reclaimed ions, ion complexes and electrical charged particles that have migrated from the soil to the housing are 25 removed with the circulation liquid. In the case of the anode, acids formed at the anode are generally also sufficiently removed by the circulation. In the case of the cathode liquid containing added acid generally needs to be circulated through the housing in order to dissolve hydroxides, or to prevent hydroxides from forming. The pH, redox potential, conductivity and 30 temperature of the liquid in circulated through the housing are measured and

controlled for this purpose, so that, to speed up the process as much as possible, a maximum electric current is supplied that can be supplied without clogging.

In practice, it has been found that occasionally during the process a 5 hydroxide crust develops on some cathodes. A thick crust makes a cathode useless, so that it has to be replaced in the ground and the remediation process effectively stops at the cathode until the cathode has been replaced.

The attractive aspect of phyto remediation is its low cost. Since 10 undesired material is collected by harvesting and does not need to be collected at the electrodes, simple electrodes may be used, which merely supply the DC current needed to induce sufficient movement around the roots, without requiring a housing through which liquid is circulated to capture material. However, without circulating liquid to remove hydroxides or acids the DC 15 current to the electrodes can only be applied for a limited time period before irreversible acidification at the anode and hydroxide forming at the cathode will take place, which makes the electrodes useless.

Heating the soil with current from electrodes can be performed with 20 AC currents, so that clogging can be avoided. However, heating the soil with current from electrodes also has its problems. In this case boiling near the electrodes can be a problem. This can lead to deposition often material such as various carbonates precipitates at the electrodes.

Among others, it is an object of the invention to increase the reliability of efficient automated operation of in situ electro remediation in soil.

25 Among others it is an object of the invention to prevent reduction in the lifetime of electrodes used during in situ electro-remediation of soil.

Among others it is an object of the invention to prevent formation of hydroxide crusts on cathodes used during in situ electro-remediation of soil.

Among others it is an object of the invention minimize the loss of processing time due to problems with electrodes during in situ electro-remediation of soil.

Among others it is an object of the invention to reduce energy 5 consumption required for in situ electro-remediation of soil.

Among others it is an object of the invention to provide for an electrical apparatus for controlling soil remediation that can be universally applied to different types of remediation processes.

A method of soil remediation according to one aspect of the invention 10 is set forth in Claim 1. This method provides for a temporary step down in electrode current through a particular electrode when upon detection of an electrical resistance increase due to increasing electrical resistance in the current path from the surface particular electrode to the soil.

Ordinarily the resistance of a current path from an electrode, in 15 particular the part of the path from the surface of the electrode to where the soil has homogeneous bulk properties, will not change in a short period. An increase of this resistance is indicative of problems at an electrode. By temporarily reducing the average current through the electrode by a significant step (e.g. by at least 10% and preferably to zero), the problems can 20 be resolved.

In the case of boiling near an electrode, the temporary cut-down allows the medium around the electrode to cool down so that the process can be resumed in a normal way.

In the case of a cathode, for example, on which precipitated 25 hydroxides cause the increase in resistance, a reduction allows acids to remove the hydroxides, because the generation of hydroxyl ions is temporarily reduced. Preferably, the average current level through the cathodes is normally controlled to the equilibrium level, or closely below the equilibrium level consistent with the supply of acid, so that the pH of the liquid around the 30 cathode assumes a dynamic equilibrium. Upon detection of the resistance

increase the average current level is reduced substantially below this current level.

Typically the current at the cathodes is cut back during a time interval of a predetermined duration between five minutes and two hours, e.g. 5 for fifteen minutes. The length of the time interval is selected dependent on the solubility of the particular hydroxide that is expected to precipitate at the cathode. This has been found to be sufficient to counteract crust formation and does not lead to excessive loss of process time.

Preferably, also, the current is cut back only at an individual 10 electrode for which a resistance increase is detected, or for a sub-group of the electrodes containing this electrode. It has been found that electrode problems generally do not occur simultaneously at all electrodes. Thus, by reducing current only at selected electrodes loss of process time is further limited.

The resistance increase can be measured in a number of ways. In 15 one embodiment information about the overall resistance between a cathode and a nearby anode is measured by measuring the average current through the anode or cathode and a voltage difference between the anode and cathode, or, if the current or voltage are known in advance, by measuring the other. If one of the current or the voltage is kept constant, the resistance need not even 20 be determined explicitly, since in this case the variable other one of the current or voltage is indicative of resistance if voltage or current is kept constant respectively. An increase in the overall resistance between anode and cathode may be used to trigger the temporary reduction.

In one embodiment the average voltages are applied between first 25 and second electrodes and the average current through the first electrodes is controlled. Thus, an equilibrium between generation of hydroxyl ions and supply of acid can be ensured at a designed level. Average current control may be realized e.g. by adapting the duty cycle with which an electric power supply source is conductively coupled to the electrodes. This technique has the 30 advantage that the supply system can easily be reconfigured to perform other

functions, for example to supply a regulated average voltage, by controlling the duty cycle, or to reverse polarity of the currents, by providing conductive coupling in during different phases of output from an AC power supply source.

In the embodiment where the average current through the first 5 electrodes is controlled information about overall resistance can be obtained from the voltage difference between electrodes. Alternatively the current through the second electrodes may be measured to obtain more accurate information about the resistance near the second electrodes.

The determination of resistance information from voltage differences 10 between anodes and cathodes, and/or of currents through these electrodes has the advantage that a minimum of electrodes is needed. However, use of the overall resistance has the disadvantage that changes in the resistance of the soil that are not related to events at the electrodes at the cathode may affect the measurement. Such changes may include pH changes in the soil, 15 precipitation of salts in the soil, temperature changes etc. To prevent this at least part of the effect of changes in resistance from the soil is preferably eliminated from the overall resistance.

The elimination of an effect of soil resistivity on detection may be realized by using at least one further electrode inserted in the soil and using a 20 voltage drop measured from that further electrode to eliminate the effect of soil resistance changes. This can be done in various ways, for example by measuring a voltage drop between a pair of sensing electrodes in a region where constant electric currents run through the soil as an indication of the resistance of the soil, and computing from this resistance how much of the 25 resistance from the cathode to the anode may be attributed to the soil. Often it may be assumed that the soil responds similarly at different locations in the treated area, and in this case the pair of sensing electrodes need not be located near the cathode for which the resistance is determined. Thus, one pair of sensing electrodes may be used to eliminate the effect of changes in soil

resistivity from measurements obtained from voltages and/or currents at a plurality of different cathodes and or anodes.

One or both of the pair of electrodes may be a properly functioning anode or cathode. In another example, the voltage drop from a cathode to a 5 nearby electrode (much closer than the nearest anode) is measured as a direct indication of the resistance near the cathode.

A method for soil remediation according to another aspect of the invention measures information is about the groundwater flow speed (e.g. by measuring a ground water level differences between mutually distant position 10 along the direction of flow) and this information is used to adapt the voltage difference between the anodes and cathodes along a line transverse to the flow direction. When the electric field in the soil is below a threshold level the electric field would be too weak so that ions from part of the ground water flow would not be deflected sufficiently far to reach the cathodes or anodes.

15 Applying an anode-cathode voltage difference that results in electric field strength above this threshold level wastes energy. The threshold level depends on ground water flow speed. By adjusting the voltage to a predicted threshold level dependent on the flow speed energy can be saved without compromising cleaning. Preferably, a control computer is provided with 20 information that makes it possible to specify the required anode-cathode voltages for the soil under process and the placement of anodes and cathodes.

Resistance variations at or near the electrodes filters may affect the anode-cathode voltage needed to produce the threshold electric field strength. In an embodiment this effect is eliminated by using at least one sensing 25 electrode in the soil, the anode-cathode voltage being adjusted until a voltage drop from the sensing electrode reaches a predicted necessary threshold level that has been predicted for the soil. Preferably the voltage drop between a pair of sensing electrodes in the soil is used for this purpose, but when most resistance variations are known to occur at one type of electrode (in particular

the cathode), the voltage drop from the sensing electrode to the other electrode (in particular the anode) may be used.

In another embodiment infiltration sources are placed at or near the row of anodes and cathodes and a current level from anodes and to cathodes is controlled dependent on the measured ground water flow speed. The relation between current level and flow speed is programmed so that sufficient material infiltrates. In a further embodiment a lower limit is imposed on the electric field between anodes and cathodes during current level selection, so that it ensured that substantially the entire groundwater flow is infiltrated.

A method for phyto remediation of soil according to another aspect of the invention reverses the polarity of the electric current between the electrodes at time points selected dependent on a measured amount of cumulative charge that has passed from one electrode to another, before the electrodes are predicted to clog. This makes it possible to use very simple electrodes without clogging.

A method for remediation of soil according to another aspect of the invention periodically interrupts the current with off-periods of at least thirty seconds. In case of heating it has been found that carbonates precipitate near the electrodes (i.e. on the surface or in the immediate vicinity of the surface), which may gather steam bubbles, which obstruct the electric current. By interrupting the current for at least thirty seconds these bubbles get the opportunity to escape. In an embodiment current for heating the soil to a desired temperature is regulated by duty cycle modulation, at least part of the off periods of the duty cycle lasting at least thirty seconds.

Preferably a versatile apparatus is provided that supports all these different methods.

These and other objects and advantageous aspects of the invention will be illustrated using the following figures.

Figures 1a,b show a first arrays of electrodes in a land area.

Figure 2 shows a second array of electrodes in a land area

Figure 3 shows an electric power supply apparatus

Figures 4a,b show voltages supplied by an electric power supply  
5 apparatus

Figure 5 shows a graph of collection efficiency as a function of voltage

Figure 6 shows a graph of threshold levels as a function of groundwater  
flow speed

10 Figures 1a,b show parts of arrays of cathodes 10 (marked by closed circles) and anodes 12 (marked by open circles) inserted in the soil in a land area. Figure 1a shows how alternate rows of cathodes and rows of cathodes may be used. Figure 1b shows how a matrix of cathodes 10 may be used, with anodes 12 each time in the middle between four cathodes 10. In addition to the  
15 anodes and cathodes in figure 1a pairs of sensing electrodes 14a,b are shown to be inserted in the soil at locations selected so that a voltage difference between anodes and cathodes results in a voltage drop between the sensing electrodes of a pair. These sensing electrodes have been omitted from figure 1b for the sake of clarity, but it will be understood that they may be used in the  
20 arrangement of figure 1b as well.

Figure 2 shows an array that may be used in a land area where there is groundwater flow (with a flow direction indicated by arrow 20). In this case a linear array of alternate cathodes 10 and anodes 12 along a line transverse to the direction of groundwater flow may be used. A pair of sensing  
25 electrodes 14a,b is shown symbolically. In addition, groundwater level sensors 22, 24 are shown upstream and downstream of the line.

Cathodes 10 and anodes 12 are inserted in the soil of a land area that is filled by the array, at positions as shown in the figures. An electrical power supply is coupled to the cathodes 10 and anodes 12, to drive electrical

current through the soil. In addition, liquid supply systems may be provided to supply liquid to anodes 12 and cathodes 10.

Figure 3 schematically shows an electrical power supply apparatus. The apparatus has cathode connections 31 for connecting individual cathodes 5 10 (not shown) and anode connections 38 for connecting individual anodes 12 (not shown). The apparatus contains a power supply source 30 such as a generator or a transformer coupled to an electricity network, cathode current switches 32, cathode current sensors 33, anode current controllers 34, anode current sensors 35, anode current feedback circuits 36, a current reference 10 source 37 and a control circuit 39.

A first terminal 30a of power supply source 30 is coupled to respective anode connections 38, each through a respective branch via a respective succession of an anode current controller 34 and an anode current sensor 35. Although a single output line is shown for first terminal 30a is 15 shown, it should be understood that in the case of an AC power supply source 30 this output line may represent a plurality of first output conductors (e.g. three), for different power supply current phases. All these output conductors for different phase outputs may be connected to each anode current controller 34, or respective phase output conductors may be coupled to respective groups 20 of anode current controller 34.

An output of anode current sensor 35 in each branch is coupled back to anode of the current controller 34 in the branch via the anode current feedback circuit 36 for the branch, which is also coupled to current reference source 37. A second terminal 30b of power supply source 30 is coupled to 25 respective cathode connections 31, each through a respective branch via a succession of a cathode current switch 32 and a cathode current sensor 33. Current sensors 33, 35 may be implemented for example as Hall sensors (known per se), which measure magnetic fields induced by the currents, or voltage sensors, which measure voltage drops over resistances in the paths to 30 connections 31, 38.

Control circuit 39 is coupled to outputs of cathode current sensors 33 and to outputs and/or inputs anode current controllers 34 (inputs and/or outputs shown as respective single lines, but it will be understood that separate lines may be used for different sensors or controller and for input and 5 output, or that a communication bus may be used). Control circuit 39 also has an input 39a for coupling to one or more pairs of sensing electrodes 14a,b (not shown).

In operation anode current controllers 34 regulate each anode current to a set level. In a preferred embodiment each current controller 34 10 contains a switch arranged to switch a conductive connection between the first terminal of electric power supply source 30 and anode connections 38 on and off, with a ratio between the part of the time during which the switch is on and off respectively so that the average anode current has the set level.

In a preferred embodiment electric power supply source 30 is an AC 15 source and current controllers 34 switch the conductive connections on and off only at the time when the output voltage levels at the terminals of electric power supply source 30 cross each other.

Figure 4a shows the voltage at an anode output connection 28 in the case where a single phase is supplied to each current controller 34. In this case 20 current controllers 34 switch on the conductive connection only during positive half cycles, when the voltage at first terminal 30a is higher than that at second terminal 30b. The connection is switched off at the time of zero crossing when there is no voltage difference between the first and second terminal 30a,b. Thus a positive half voltage phase 40 is applied to anode connections 38. 25 Current controller 34 does not pass all positive half phases provided by power supply source 30. The fraction of half cycles during which the conductive connection is on is dependent on the required average anode current.

Figure 4b shows the voltage at an anode output connection 28 in the case where three phases are supplied to each current controller 34. In 30 respective cycle parts 42, 44, 46 the voltage is determined by establishing a

conductive connection to respective ones of the phase output conductors of first terminal 30a. In this case current controllers 34 switch on the conductive connection from respective phase output conductor of first terminal 30a alternately, or switch all conductive connections off. Current controllers 5 select the time of transitions between on and off cycle parts 42, 44, 46, at the time of crossing with the next voltage that is switched on or, if all connections are switched off, at the time of zero crossing of the voltage of the last connected phase output conductor with the voltage at second terminal 30b. The connections are kept switched on only while the voltage at the connected phase 10 output conductor is higher than that of second terminal 30b. During part of the time current controller 34 does not connect any of the phase output conductors to an anode output connection 38, or at least not the phase output conductor that has the highest voltage. The fraction of cycle parts during which the conductive connections between the output phase conductors and anode output 15 connection 38 is on is dependent on the required average anode current.

The apparatus may be applied to drive various processes in the soil, including for example electrokinetics and heating. The use of electrokinetics for soil remediation is described in US patent No 5,433,829. Prior to installation of the electrodes and the apparatus exploratory measurements are performed 20 (usually including sampling and measurements on samples) to determine soil properties such as electrical soil resistivity, response to electric current and soil composition. Dependent on the results of the measurements a method of treatment is selected. For a give method of treatment parameters of the remediation process are selected, such as the number of anodes 12 and 25 cathodes 10 and the mutual distance at which these anodes and cathodes will be placed in the soil, the size of currents that will be passed from the anodes 12 and cathodes 10 into the soil and the duration of the remediation process.

The selectable size of the current is limited by the risk of corruption 30 of the anodes 12 and cathodes 10. When high currents (e.g. 10 Ampere per meter of anode or cathode) are used it is generally necessary to supply liquids

to the anodes 12 and cathodes 10. US patent No 5,433,829 describes how the anodes 12 and cathodes 10 can be placed in the ground in containers through which liquid is circulated, the containers having walls that are permeable for charged particles but much less permeable for the bulk of the liquid. In the 5 case of anodes 12 the liquid typically is water (if necessary with an added base to improve the removal of acids, but usually normal water suffices). In the case of cathodes 10 the liquid generally contains an acid in order to compensate hydroxyl ions generated by the currents through the cathodes 10. In this case the maximum useful current is determined by the rate at which 10 hydroxyl ion scan be removed by the circulating liquid.

Preferably, two liquid circulation systems are provided: one for the cathodes and one for the anodes. Liquid is pumped from storage tanks through conduits that are connected to the electrode containers and back from the containers to the storage tank. pH of liquid supplied to cathodes or anodes can 15 be controlled by controlling an flow of acid or base from a supply vessel to the circulating liquid. Conductivity, redox potential and contaminant concentrations can be controlled by the rate of refreshing the electrolyte. Temperature in the soil and near the electrodes can be controlled by temporarily cut off current. In the anode electrolyte: pH can be controlled by 20 adding Ca(OH)2, NaOH, and redox potential can be controlled by adding Ca(OH)2, NaOH. Conductivity can be controlled by refreshing the electrolyte. Contaminant concentrations can be controlled by refreshing or treating the electrolyte

The various possible processes that may be controlled with this 25 apparatus will now be described in more detail.

### Electrokinetic processing

In general the electrokinetic process is used when contaminants 30 have to be removed from the soil. Under influence of the electric field between

the anodes 12 and cathodes the contaminants move through the soil to the anodes or cathodes, where they are captured.

Of the contaminant(s) to be removed, it is preferred that the chemical structure, the form in which the contaminant is present (bound to the soil, liquid phase, solid phase, dissolved in the ground water), the distribution over the site and/or the concentration of the contaminant(s) are determined. For efficient decontamination, it is preferred that not only the amount of contaminants is determined but also the total quantity of charged particles in the soil, and/or the electric conductivity of the soil.

For effective decontamination it is preferred that the contaminant is mainly present in a charged state (as an ion, ion complex, etc), because the electrokinetic velocity of the contaminant is directly proportional to the electric field strength and its effective electrophoretic or ion mobility, the latter being dependent on the effective charge of the contaminant.

The speed at which decontamination takes place may be influenced by altering the effective mobility, such as by changing the pH. In case of removal of heavy metals, the pH is preferably acidic, to ensure a high charge and suppress binding to the soil material. During the electrokinetic process the pH may be brought to a desired value, *e.g.* by electrokinetically transporting acid/base from electrode liquid (or a liquid injected near an electrode) through the soil. In general the pH is preferably decreased in case of heavy metals (*e.g.* to a value in the range of 1 to 5 for instance about 3), and the pH is preferably increased in case of contaminants such as arsenic or cyanide (*e.g.* to a value in the range of XX8 to XX12 for instance about 10). Before the electrokinetic decontamination a suitable (or optimal) pH is determined in the laboratory by altering the pH and checking the electric conductivity and the concentrations of the contaminants in the soil water. The soil is mixed with acid or base and the required quantity of gram equivalents protons or hydroxyl ions, needed for a specific pH change may be determined. This information can be used to

regulate the pH during the electrokinetic step, by using the H<sup>+</sup> and OH<sup>-</sup> formed at the electrodes due to electrolysis.

One or more acids, bases and/or complexing agents may be supplied at the beginning and/or during the electrokinetic process. The choice of such 5 additives may be based upon the lab tests. The skilled person will know how to perform such tests and how to choose appropriate additives based upon common general knowledge and the information disclosed herein, dependent on the type of contamination, soil composition etc.

Further, electrokinetic lab tests may be performed with samples of 10 contaminated soil material, which may or may not be mixed with acid/base/complexing agents. The samples may be evaluated for their decontamination speed under different conditions, such as at different current densities (A/m<sup>2</sup>).

For example, for clay-like or sand with relatively small particles 15 very good results have been achieved at a pH of about 3. The gram equivalent amount protons per m<sup>3</sup> needed to reduce the pH to 3 has been found in a range e about 100 – 2000 gramequivalent H<sup>+</sup> /m<sup>3</sup>.

The results of the electrokinetic tests and the exchange tests can be used into a calculation model, that can be used to determine the practical 20 conditions for the decontamination. The electric charge (Ampere second or Faraday) per volume unit of soil material that has passed, is an indication for the progress of the decontamination.

Changes in temperature, acidity, solubility of contamination and other substances, humidity etc, that occur in the soil and at the electrodes 25 during remediation have an effect on the electrical conductivity of the soil material. These changes are relatively slow and may be predicted and monitored with current and voltage measurements.

The electrode containers can be inserted horizontally, vertically or at an angle in the soil. The container of the electrode may be made of ceramic 30 material, or surrounded with a layer that is permeable for charged particles

but much less for uncharged particles (e.g. Bentonite) if only electrically charged particles should be transported from the soil. . Apart from ceramic material tubes of PVC- PE en HDPE may be used. The supply and abduction conduits for electrode liquids can be made of the same type of material.

- 5 Connections for these conduits to the electrode housings depend on the way the electrodes are placed and other local circumstances, such as groundwater level, the need to place the conduits underground etc. Circulation of liquid should take place along the entire active electrode surface. This can be realized with electrostatic pressure difference between supply and abduction conduits,
- 10 by pumping or pressurizing. Anode materials such as graphite, noble metals, titanium or ebonex coated with noble metals may be used for the processes involved. The implementation depends on the electrode housing. To prevent energy loss and undesired heating a large electrode surface is desirable. Useful shapes are bars, wires, cables plates or grids. The cathode may contain
- 15 graphite, (stainless) steel etc., dependent on the type of contaminants and may have the shapes mentioned for the anodes.

Once the desired current has been selected the anodes and cathodes have been inserted into the soil. The anodes and cathodes may then be connected to the anode and cathode connections of the apparatus of figure 3

- 20 and the apparatus may be set to supply on average the selected current to the cathodes.

Control circuit 39 monitors whether anodes 12 and cathodes 10 function properly and causes the apparatus to intervene if this is not the case. Current controllers 34 determine information about the average output

- 25 voltages supplied to respective anode connections 38. This information is sent to control circuit 39. In the case of current control by on/off switching the information about the average output voltage may be information about the fraction of time that the current is "on".

Cathode current sensors 33 sense the average currents drawn by respective cathode connections 31 and provide information about these currents to control circuit 39.

Control circuit 39 is typically implemented as a suitable 5 programmed micro-controller. In one aspect control circuit 39 monitors whether increases occur in the resistance of the paths from individual cathodes 10 into the soil. When such an increase for a particular cathode 10 exceeds a predetermined threshold level, control circuit 39 causes the cathode current switch 33 of the connection 31 to this particular cathode 10 to block current 10 from the particular cathode 10 for a time interval of predetermined length, e.g. fifteen minutes.

The increase of resistance is taken to be a signal that hydroxides precipitate at or near the surface of the cathode. This may be the result for example of locally different properties of the soil near the cathode (e.g. a locally 15 higher concentration of Ca ions) or of fluctuations in acid supply. If the precipitation process would be allowed to proceed too long at a cathode, a crust would form on that cathode that makes the cathode irrevocably useless. By temporarily cutting of the cathode current the formation of hydroxides is interrupted and the acid from the circulating gets the opportunity to dissolve 20 the precipitated hydroxides.

Of course, the invention is not limited to this implementation or indeed to the particular circuit of figure 3. For example, it will be understood that instead of using current control circuits for individual anodes, current control circuits may be provided for individual cathodes. In this case the 25 current at the cathode may be adjusted directly.

As another example, instead of cutting off the cathode current to a particular cathode altogether, the cathode current may be merely reduced to a level substantially (e.g. at least 10%) below the level at which there is an equilibrium between the rate of generation of hydroxyl ions due to the current 30 and their removal by the circulating liquid with acid. The reduction can be

realized by switching off the cathode switch 33 of a particular cathode for which an increase of resistance has been detected with a corresponding duty cycle. In another embodiment the cathode current from a particular cathode may be reduced by switching off, or reducing, the current from one or more 5 anodes that have been inserted in the soil near the particular cathode.

For this purpose control circuit 39 preferably has available information that indicates which of the anode connections 38 has been connected to an anode that has been inserted in the soil near the cathodes that are connected to specific ones of the cathode connections 31. This may be 10 realized by storing information about the position of the cathodes and anodes in control circuit 39. Alternatively, it may be required to connect anodes and cathodes that have been inserted in the ground near to one another to predetermined pairs of an anode connection 38 and a cathode connection 31, control circuit 39 reducing the current to the anode connection 38 of a pair 15 when the resistance of the cathode connected to the cathode connection of a pair increases.

Preferably, the current to cathodes for which substantially no resistance increase is detected is maintained at the normal level while the current is reduced for selected cathodes. Alternatively, the current to the 20 entire array of anodes and cathodes, or to a subgroup of a plurality of cathodes and/or anodes may be temporarily switched off or reduced. But this is not necessary, since it has been found that precipitation of hydroxides does not generally start at the same time at all cathodes. Therefore switching off many cathodes each time when one cathode has increased resistance would lead to 25 unnecessary production loss and longer process duration. This is preferably avoided by switching off or reducing the current only to selected electrodes.

When the resistance near a particular cathode increases repeatedly it may be desirable to adjust the current supplied by nearby anodes 30 permanently by a small amount (e.g. in a step of 1%) to prevent hydroxide formation so that the cathode does not have to be switched off too often.

The determination of the resistance increase at or near the surface of the cathodes can be realized in various ways. In a preferred embodiment, information about the resistance between a cathode and a nearest anode is used to decide whether to reduce the current through that cathode, after 5 correction of the effect of the resistivity  $\rho$  of the soil. Correction for the effect of the resistivity  $\rho$  of the soil is desirable because this resistivity  $\rho$  can change during the process, for example due to chemical or physical changes in the soil due to the current and/or external factors.

When each of the anodes supply a controlled current  $I$  an indication 10 of the resistance of the cathode plus that of the soil can be obtained from the voltage difference  $V_{ac}$  between the cathode and a nearby anode (or between the voltage at the cathode and average of voltages at nearby anodes):

$$V_{ac} = I \times (R_{soil} + R_{cathode})$$

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Control circuit 39 preferably substantially eliminates the effect of changes in the contribution  $R_{soil}$  of the soil, for example by subtracting a prediction of  $I \times R_{soil}$  from  $V_{ac}$ . Control circuit 39 can make this prediction by using a measured 20 value  $V_{drop}$  of a voltage drop between a pair of test electrodes 14a,b that have been inserted in the soil in the vicinity of the anode and the cathode under consideration. Assuming that the constant current  $I$  supplied to the anodes leads to a constant current density  $J$  in the soil, the voltage drop  $V_{drop}$  is proportional to the resistivity  $\rho$  of the soil times this current density. As a result  $I \times R_{soil}$  can be predicted by multiplying  $V_{drop}$  by a factor  $\lambda$ :

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$$I \times R_{soil} = \lambda V_{drop}$$

Hence, the difference  $V_{ac} - \lambda V_{drop}$  may be used as an indication of the 30 resistance near the cathode, where  $\lambda$  depends on geometrical factors, such as the distance between the test electrodes and the distance between the anodes

and cathodes.  $\lambda$  does not depend on the properties of the soil, so that it can be set once in control circuit 39, for subsequent use.

Preferably, coordinates of the sensing electrodes relative to the anodes and cathodes and/or coordinates of the anodes and cathodes are used to 5 compute  $\lambda$  for each given pair of sensing electrodes. This computation may be performed by control circuit 39, which receives the coordinates for this purpose. Alternatively, the computation may be performed off-line,  $\lambda$  values being entered in control circuit 39 for respective pairs of electrodes. In another embodiment control circuit 29 is preprogrammed with  $\lambda$  values for sensing 10 electrodes at specified positions and the sensing electrodes are inserted at those positions.

It may be noted that the elimination of the effect of the resistivity of the soil need not be perfectly accurate. It suffices that most of the effect of resistivity of the soil is eliminated, so that the effects of resistance changes due 15 to the precipitation of hydroxides in an amount that can still be removed by the acid in the circulating liquid exceed the effect of the resistivity of the soil. Therefore  $\lambda$  need only be known approximately. As an alternative, a ratio  $V_{ac} : V_{drop}$  is determined as an indication of the resistance near the cathode. This ratio still depends slightly on soil resistivity, but less than  $V_{ac}$ , so that it can be 20 used as a more reliable criterion for cathode resistance with knowledge of  $\lambda$ .

In general, it is expected that the resistivity  $\rho$  of the soil varies only slowly as a function of time and position in the land area in which anodes and cathodes have been inserted. Therefore, it is generally not necessary to place different pairs of test electrodes 14a,b near each particular cathode. 25 Measurements of  $V_{drop}$  obtained from a pair of test electrodes 14a,b that has been inserted into the soil nearer to another cathode may be used to eliminate the effect of soil resistance on the voltage  $V_{ac}$  obtained for a particular cathode. Thus much fewer test electrode than anodes and cathodes suffice.

It should be appreciated that elimination of the effect of the 30 resistivity of the soil can be realized in other ways. For example, a test

electrode may be inserted in the soil near each cathode outside the cathode housing. In this case control circuit 39 may use the voltage drop between the cathode and the nearby electrode as an indication of the resistivity near the cathode. As another example, a time profile of the changes of the resistivity of 5 the soil may be predicted from laboratory experiments with a sample of the soil. This time profile can be programmed into control circuit 39 and used to correct effect of the resistivity of the soil similarly as described in the preceding.

In yet another alternative information about the resistivity of the soil may be obtained by measuring the resistance between a pair of anodes, 10 e.g. by imposing a test voltage between two anodes while the current to nearby other electrodes is temporarily switched off. In another alternative, control circuit 39 may use the difference  $V_{ac}^{(1)} - V_{ac}^{(2)}$  between the anode-cathode voltages  $V_{ac}^{(1)}$ ,  $V_{ac}^{(2)}$  of different anode-cathode pairs while predetermined currents are supplied, to determine whether a resistance increase near the 15 cathode of one of the pair occurs. In another example, the difference between the average current through a particular cathode and an average of the currents through nearby cathodes may be used as an indication of an increase in resistance.

20

### Electrokinetic screen processing

A so-called hydrological screen has been proposed in the art to stop 25 contaminations in ground water flows or to capture such contaminants. This screen is formed by pumping (contaminated) ground water to the surface. A disadvantage of such a screen is the large amount of water that usually needs to be pumped and that subsequently needs to be purified in a water decontamination process.

Alternatively or in combination with a hydrological screen, an 30 electrokinetic screen may be employed. Such screen does not have the disadvantage of having to purify large amounts of water. The electrokinetic

screen is formed by electric fields between alternating electrodes as shown in figure 2. The electric fields are typically applied transverse to the flow direction of the ground water. Preferably the screen is applied essentially perpendicular to said flow direction.

5 The electrokinetic screen can be used to capture charged contaminants, for instance heavy metals or cyanides. In the electric field the direction of movement of such compounds occurs at an angle to the direction of ground water flow, so that the compounds reach the electrodes rather than continuing to flow with the groundwater stream. The electrodes are usually 10 placed in a housing, which is filled with circulating electrode liquid to remove the trapped compounds. Basically, the operation is similar to that during electrokinetic treatment, except that it suffices to provide electrodes only along a line instead of an area, because the groundwater flow ensures that the 15 contamination is moved to that line. An important advantage of using a electro screen is the low volume of electrode liquid that needs to be treated to remove the contaminant, and which is in general comparable to a water treatment in electrokinetic decontamination.

For satisfactory removal of the contaminants a sufficiently strong average electric field strength of constant polarity (DC) is generally needed in 20 the soil. If the electric field strength is too small part of the contaminants will not be sufficiently be deflected to reach the electrodes before the contaminants are carried on by the groundwater flow.

Figure 5 illustrates this effect with a graph of the fraction  $x$  of captured contaminants as a function of anode-cathode voltage  $V_{ac}$ . As can be 25 seen the fraction  $x$  increases with the voltage  $V_{ac}$  until a critical field strength  $E_c$  is realized in the soil, above which substantially all contaminants are captured. This critical field strength depends on the charge and mobility of the contaminants in the soil and on the flow speed of the groundwater flow.

Figure 6 illustrates a graph of a prediction of the critical field 30 strength  $E_c$  as a function of groundwater flow speed  $u$ . Given measurements of

the properties of a sample of the soil this prediction can be made by mathematical methods known per se e.g. from Schaum's on line series on Electrical Power Systems van Syed A. Nasser (1990, ISBN 0-07-0459177) Chapter 3. The prediction can also be determined experimentally, on 5 laboratory scale or in field application for example by observing the amount of collected contaminant for different electric fields and groundwater flow speed.

During electrokinetic screen processing the apparatus that applies electric voltages to the anodes and cathodes receives information about the groundwater flow speed and adjusts the anode-cathode voltage difference to 10 the received information. In principle, the apparatus of figure 3 may be used, wherein the current controllers 34 contain switches and the current control loops with control circuit 36 are deactivated. In this case control circuit 39 controls the switches in current controllers 34 so that the average voltage (i.e. the fraction of time that the switches in current controllers 34 conduct) is 15 adapted dependent on the information about groundwater flow speed. Control circuit 39 uses an internal memory (not shown separately) wherein information has been programmed that determines the required anode-cathode voltages that will be applied as a function of groundwater flow speed. The required voltages correspond to the critical field strengths (or in general 20 slightly higher field strengths) that have been predicted for the particular soil and contamination under treatment and correspond essentially to figure 5. Any convenient representation may be used to represent the dependence on groundwater flow speed, such as a table of voltage values for different flow speeds, or coefficients of a polynomial function that expresses field strength as 25 a function of flow speed, or any other set of parameters that specifies such a function. Control circuit 39 sets the time averaged anode-cathode voltage, to the voltage for the measured flow speed, as determined by using information from the memory. As a result the voltage is substantially equal to or slightly higher than needed to realize the critical field strength at the measured flow 30 speed.

It may be appreciated that the adaptation need not be instantaneous. Common average groundwater flow speeds are very small (of the order of 1-100 meters per year) so that it suffices that the time averaged voltage is substantially equal to the voltage needed to realize the average 5 critical field strength over a timescale of weeks or months only.

Information about the groundwater flow speed may be obtained by measuring the difference between ground water levels at positions upstream and downstream from one another e.g. near the screen. The ground water level difference is proportional to the ground water flow speed and may be used 10 directly to regulate the electric field between any two electrodes. Of course other measurements of groundwater flow speed may be used, such as temperature gradients etc.

Preferably the apparatus (and in the case of the apparatus of figure 3 control circuit 36) also receives information about a voltage drop between a 15 pair of sensing electrodes placed in any soil region where an anode and cathode pair generates a measurable electric field. In this embodiment control circuit 36 stores information about the voltage drops that have to be realized between the sensing electrodes for respective measured flow speeds. The specified voltage drops correspond to the critical field strengths, or are slightly higher. 20 The apparatus adjusts the anode cathode voltage so that the measured voltage drop between the sensing electrodes reaches a specified level for the measured groundwater flow speed. Use of this type of voltage drop measurement eliminates the effect of changes due to resistances changing at or near the electrodes. It will be appreciated that, instead of the voltage drop between a 25 pair of sensing electrodes, the voltage drop from a sensing electrode and one of the anodes or cathodes may be used, if it is predicted that resistance variations near that anode or cathode do not significantly affect the measurement. This is often the case for anodes.

### Electrokinetic bioscreen processing

Soil material containing uncharged organic contaminant(s), for instance halogenated hydrocarbons, such as per- tri- and dichloroalkylenes 5 (e.g. per- tri- and dichloroethylenes) may be decontaminated in accordance with the invention by biological degradation. Biological degradation thereof may be accomplished by applying a electrically charged carbon source such as lactate, acetate, citrate or the like, a charged nitrogen source such as ammonium chloride and/or a charged phosphor source such as (sodium hexa 10 meta)phosphate through the soil by means of electrokinetic migration. Microorganisms in the soil are then capable to adequately degrade organic contaminants. Anaerobic microorganisms have been found very suitable for removing Perchloro-ethylene, Trichloro-ethelene etc.

Aerobic microorganisms are suitable for removing organic 15 contamant(s) like PCA (polycyclic aromates) ,BTEX contaminants (benzene, toluene etc.). In this case Nitrates, hexamataphoshates may supplied electrokinetically through the soil.

The electric field used for the electrokinetic migration, which usually has a constant polarity (DC), is referred to as an electrokinetic bioscreen. 20 Configurations as shown in figures 1 and 2 may be used. Infiltration filters, comprising said carbon, nitrogen and/or phosphor source(s) may be part of the anode and/or cathode assemblies, or separate infiltration filters may be placed in the soil within the influence sphere of the electrodes. When there is a groundwater flow the infiltration filters are preferably placed upstream of the 25 electrodes (in view of the ground water flow). An advantage of using infiltration filters is the reduction in energy that is required to keep the bioscreen intact.

During electrokinetic bioscreen processing the apparatus that applies electric voltages to the anodes and cathodes receives information about

the groundwater flow speed and adjusts the anode-cathode current or voltage difference to the received information.

The amount of nutrients electromigrated from the anode and cathode into the soil is proportional to the cumulative amount of current 5 through the electrodes. The amount of nutrients needed for biodegradation of the contaminants are calculated from laboratory measurements of the concentration of these contaminants and from field measurements of the amount of groundwater flowing through the screen. In the laboratory test the efficiency per Faraday can be estimated of each component of a desired 10 mixture of nutrients. Thus, a minimum of current through a pair of electrodes (anode and cathode) is required in the case of the electrokinetic biosecreen. In addition also the critical electric field related to the groundwater flow is important to ensure that nutrients move through the entire width of groundwater flow through the screen.

15 In this case, the apparatus is arranged so that both at least the critical field strength and at least the required minimum current are realized. If sufficient current flows when the critical field strength is realized, the anode-cathode voltage is kept at or slightly above the level needed to realize this field strength. If insufficient current flows when the critical field strength 20 is realized, the anode-cathode voltage is raised to a level that results in sufficient current, above the level needed to realize the critical field strength.

Generally, for a specific soil either the first or the second type of anode cathode voltage control is needed, so that the apparatus can be arranged to perform one form of control accordingly. In some soils, a cross-over may 25 occur so that there is a critical ground water flow speed above which one type of anode cathode voltage control is needed and below which the other type of anode cathode voltage control is needed. In this case, the apparatus can be programmed to select the appropriate type of control, for example by providing for a minimum anode-cathode voltage and regulating voltage to a higher level 30 if the current is below the required level.

In principle, the apparatus of figure 3 may be used. In this case control circuit 39 controls the reference current source 37 so that the average current is adapted dependent on the information about groundwater flow speed.

5 Control circuit 39 uses an internal memory (not shown separately) wherein information has been programmed that determines the required anode-cathode voltages and/or current that will be applied as a function of groundwater flow speed. The required voltages correspond to the critical field strengths (or in general slightly higher field strengths) that have been  
10 predicted for the particular soil and contamination under treatment and correspond essentially to figure 5. The required currents correspond to the current (or in general slightly higher currents) that have been predicted to be needed to transport sufficient nutrients for the particular soil and contamination under treatment. Any convenient representation may be used  
15 to represent the dependence on groundwater flow speed.

Control circuit 39 is arranged to set the time averaged anode-cathode voltage as described before or it activate current regulation to the level required for the measured flow speed, as determined by using information from the memory. Alternatively control circuit 39 may be arranged to activate  
20 and deactivate current regulation, the current regulation being deactivated when the average anode-cathode voltage is below the required level for the measured ground water flow speed, after which the voltage is regulated, the current regulation being activated if the average current is below the required level for the measured ground water flow speed.

25 It may be appreciated that the adaptation need not be instantaneous. Common average groundwater flow speeds are very small (of the order of 1-100 meters per year) so that it suffices that the average voltage and current are above the average critical voltage and current over a timescale of weeks or months only. Similarly, it may be appreciated that one or more

sensing electrodes may be used to permit regulation of field strength in the soil independent of resistance variations at the anodes and/or cathodes.

### **Electro phytoremediation processing**

5

Phytoextraction is suitable in case of diffuse contaminations, which may for instance be the result of deposition of contaminants, such as heavy metals from the air. Fast growing plant such as rape or a grasses are repeatedly sown. The growing plants collect a part of the heavy metals. The 10 heavy metals are removed by harvesting the plants (e.g. every three months or so).. Phytoextraction is laborious and time consuming because a plurality of sowing/harvesting cycles is usually required for removing a substantial amount of the contaminants, due to the limited influence sphere of the root system of the plants.

15

The efficiency can be improved by combining phytoextraction with an electrokinetic treatment. Thus metals are mobilised and allowed to migrate through the soil that contains the root system of the plants, thus in effect increasing the sphere of influence of the root system. Thus, an electric field improves the efficiency of phytoremediation.

20

Because the contaminants do not need to migrate towards an electrode, a relatively simple electrode construction may advantageously be used in this case. Anodes and cathodes encased in bentonite may be used for example, without liquid circulation system. To obtain the required migration of contaminant(s) through or near the root zone of the plants a DC voltage may 25 be applied. However, when the anodes and cathodes have no circulation system there is a risk of electrode clogging. Use of Bentonite around the electrodes can increase the time interval until clogging occurs, because Bentonite has a buffer capacity for receiving protons at the anode and hydroxyl ions at the cathode. Other materials may be used that have similar buffering 30 properties. However, even in this case clogging will occur.

This can be prevented by regularly changing the polarity of the current. The selection of the frequency of such polarity changes requires a trade-off. A relatively high frequency reduces the risk of clogging, but it minimizes the distance over which contaminants are transported, thereby 5 reducing efficiency. On the other hand a low frequency increases efficiency at the expense of an increased risk of clogging.

A suitable moment to switch polarity may be determined based upon the mobility of the contaminant(s) and the applied electric field strength. Preferably, the moment at which to switch the polarity is determined based 10 upon the charge, i.e. the integral of the current, that has passed the electrode since the last switch (or since starting the process). Using samples of the soil a safe charge is determined that can be passed without risk of clogging, preferably taking into account the pH-buffering capacity of the material (e.g. the bentonite) around the electrodes. The polarity is reversed each time this 15 charge has been reached. It has been found that thus the pH is kept at a favourable value, especially in the vicinity of the electrodes.

During phytoextraction processing the apparatus that applies electric voltages to the anodes and cathodes receives information about current and integrates the current to select the time of polarity reversal. In principle, 20 the apparatus of figure 3 may be used, wherein the current controllers 34 contain switches. Dependent on a selected polarity control circuit 39 commands switches in current controllers 34 to conduct current only when the first terminal of power supply source is positive relative to the second terminal or when the first terminal of power supply source is negative relative to the 25 second terminal. The current control loops with control circuit 36 may be activate, but this is not necessary.

Control circuit 39 receives information about the anode and/or cathode current from sensors 33, 35 (if the anode current is controlled no sensor information from anode current sensors 35 is needed). Control circuit 39 30 stores a programmed charge threshold value and integrates the current until

any of the electrodes has reached the charge threshold value. If so control circuit changes the selected polarity. In practice the polarity is typically changed after a period of half a day to a couple of days, depending on the circumstances.

5 In principle, the cumulated charge may be measured for a plurality of electrodes individually, the polarity being reversed for the entire array when any one of the measured charges reaches a threshold level. Thus, local variations in the soil can be accounted for. Alternatively, cumulative charge for a single anode or cathode or joint charge for a group of anodes or cathodes may  
10 10 be used to trigger polarity reversal, assuming homogeneous conditions in the ground.

In practice, it has been found advantageous to combine an electrokinetic technique such as described herein with electrophyro-remediation. Such process may suitably be carried out using electrodes, which  
15 15 preferably are positioned essentially horizontally, spaced apart several meters (in particular about 2 to 20 m, wherein the electrodes (e.g. of stainless steel, ebonex<sup>TM</sup>, coated titanium) are optionally placed in a housing which housing is optionally provided with moist or another electrically conductive material with ion buffering capacity (e.g. bentonite). The electrically conductive material is  
20 20 preferably used in order to ensure a good contact between soil and electrodes and to provide a certain buffer capacity for the produced protons at the anode and hydroxyl ions at the cathode).

The electric voltage) between the electrodes is preferably regulated by monitoring the electrical potential over a part of the soil material (using one  
25 25 or more sensing electrodes as described above), so that a desired field strength is realized. The required field strength is selected on the basis of a trade-off. The roots of the plants are able to absorb contaminants at a certain rate only. If the electric field is too high a fraction of the contaminants will be moved on from the roots before it can be absorbed. Thus, electric power is wasted. If the  
30 30 electric field is too small the contaminants will be depleted before they are

replace under influence of the electric field, making it necessary to have many harvests. The field strength is selected so high that the rate of supply of contaminants under influence of the electric field substantially matches the maximum possible take-up rate of the roots. The required electric field is 5 calculated from information about the plants and laboratory measurements of the mobility of contaminants. Calculation methods for that purpose are commonly known in the art.

The desired electrical voltage difference between the electrodes is set to the calculated value based upon the mobility of the contaminant(s).

10 An important advantage of electro-phytodecontamination is the low electrical power that is required in comparison to a process wherein only use is made of electrokinetic decontamination. In particular, electro-phyto decontamination may very suitably be used with a system operating on a sustainable energy source, for instance wind energy or solar energy. Thus, 15 such a process is very interesting in (remote) areas wherein no regular energy source is available.

### Soil heating processing

20 Heating of the soil material can contribute to an accelerated decontamination both in biological conversion and in chemical oxidation techniques. Direct heating by electrical soil heating is very suitable, even in case of poorly permeable soil materials. Both AC and DC currents can be employed. Use of DC currents allows for electromigration of additives such as 25 nutrients respectively oxidizing agents (in particular electrically charged additives) throughout the soil material. Soil heating by a process according to the invention has been found very suitable in for promoting the decomposition of a contamination from medium, in particular water or air from the soil material.

For solely heating the soil an AC voltage is preferred. The electrolysis at the electrodes has been found considerably less than with a DC voltage or even completely absent. Heating may very suitably be carried out without using recirculation of electrode liquids, if used at all. Preferred 5 electrode materials are selected from iron, steel and graphite. Preferred shapes are selected from tubular shape, rod-shaped, bar-shaped and cable-shaped.

Preferably, the electrode, in particular in case of a metal electrode, is placed in a holder to avoid direct contact of the electrode with the soil. Thus 10 deposition of minerals such as clay minerals or carbonates on the electrodes is avoided or at least reduced. Suitable holders include ceramic filters and plastic filters wherein the electrode is placed together with graphite particles to allow a sufficient conductance.

The dimensions and configuration of the electrodes can be chosen depending upon the conditions. The skilled person will know how to choose 15 these appropriately. For instance the electrodes may be placed vertically, horizontally or at an angle with the soil. The energy may be taken from a mains circuit or an electro-generator. In case of an AC voltage, it may be supplied in 12 phases, 6 phases, 3 phases, one phase or otherwise. Good results have *inter alia* been achieved with electrode configuration in a triangular or 20 hexagonal set-up.

In general heating tends to be highest near the electrodes, because of the high current density. In order to prevent drying up or even boiling of the vicinity of the electrodes, the current through each electrode or at least through a number of the electrodes is regulated.

25 During heating the apparatus that applies electric voltages to the electrodes regulates the current, for example so that on average a specified temperature or at most a specified temperature occurs in the soil, which is compatible for example with PVC conduits in the soil

In principle, the apparatus of figure 3 may be used. When AC field 30 are used during heating complete cycles of the electric voltage from supply

source 30 may be passed through current controllers 34. The average current is regulated by selecting the fraction of cycles, or half cycles of supply source 30 in which current is conducted to connections 38. Since AC current is preferably used, preferably the same number of positive and negative cycles is passed,

5 e.g. by passing selected full cycles of the AC signal from supply source 30.

Preferably, current controllers 34 are arranged to select the cycles so that time intervals of at least one minute exist in which no current is passed. It has been found that this promotes the release of steam bubbles from the electrodes, which lowers the resistance of the electrodes.

10 Boiling near the electrodes may be detected and counteracted as electrode clogging described for electrokinetic processing.

15 Optionally a supply of water is operated at the vicinity of the electrodes to regulate the humidity of the vicinity of the electrodes. Control circuit may activate the supply of water when boiling is detected near the electrodes. Another measure against drying up is supplying water around the electrodes to counteract the water loss and the use of a material like Bentonite around the electrodes.

20 Electric heating may be combined with *in situ* chemical oxidation of contaminant(s). An increased temperature usually results in an acceleration of the oxidation rate or helps to start the reaction, e.g. if a peroxide is used. Good results have *inter alia* been achieved with a process wherein the temperature of the soil is raised to a value in the range of about 35-45°C.

25 It will be appreciated by now that the apparatus shown in figure 3 can be applied to various different forms of *in situ* soil processing. Preferably the apparatus is installed in a closed unit, for example in the form of a ISO standard size container, which can be driven to a land area that needs to be treated, connected to electrodes (including anodes and cathodes) that have been inserted into the soil and left there operating for months or years to treat the soil according to any selected process.

No separate, different apparatuses are needed for different forms of processing. Dependent on the selected process different forms of control are used and different information may have to be programmed into control circuit 39. Control circuit 39 may contain programs to perform all described forms of 5 processing, a particular form being selected by an external command when the apparatus is activated, or the appropriate program may be loaded when the apparatus is activated.

However, it should be appreciated that instead of an AC power supply source a DC power supply source may be used. In this case, the average 10 current or voltage may be regulated by adjusting a duty cycle during which this DC power supply source is connected to the anodes and/or cathodes. Reversal of polarity can be realized by commuting the output connections to the DC power supply source.